Diagnosing Vertical Motion in the Equatorial Atlantic

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Tropical Atlantic and PIRATA-15 meeting
2-5 March 2010
Miami, Florida

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The Regional Model

(*Giordani et al., 2005a,b*)

•Primitive Equation Model implemented in the Atlantic Equatorial region

•Atlantic Cold Tongue development during EGEE-3

•Processes studies ⇒ How works the Equatorial upwelling ?

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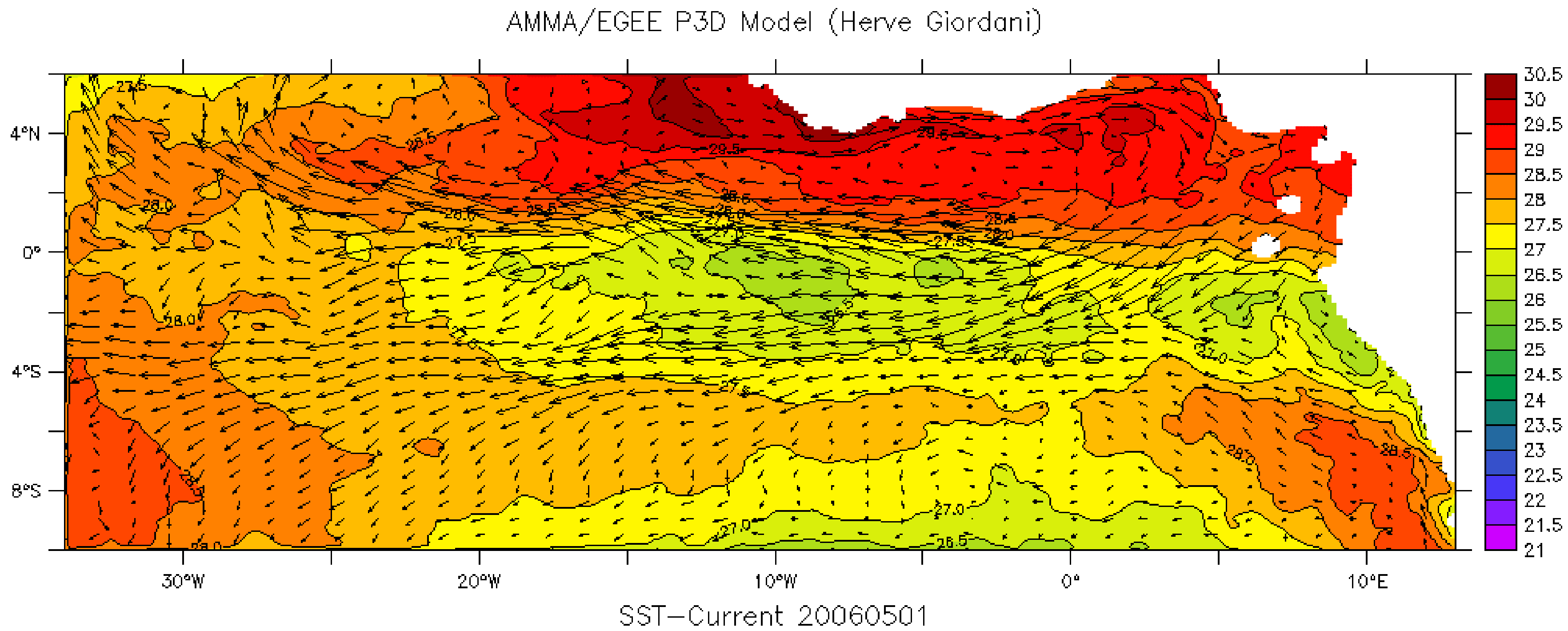
Simulation: MJJA 2006



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Validation

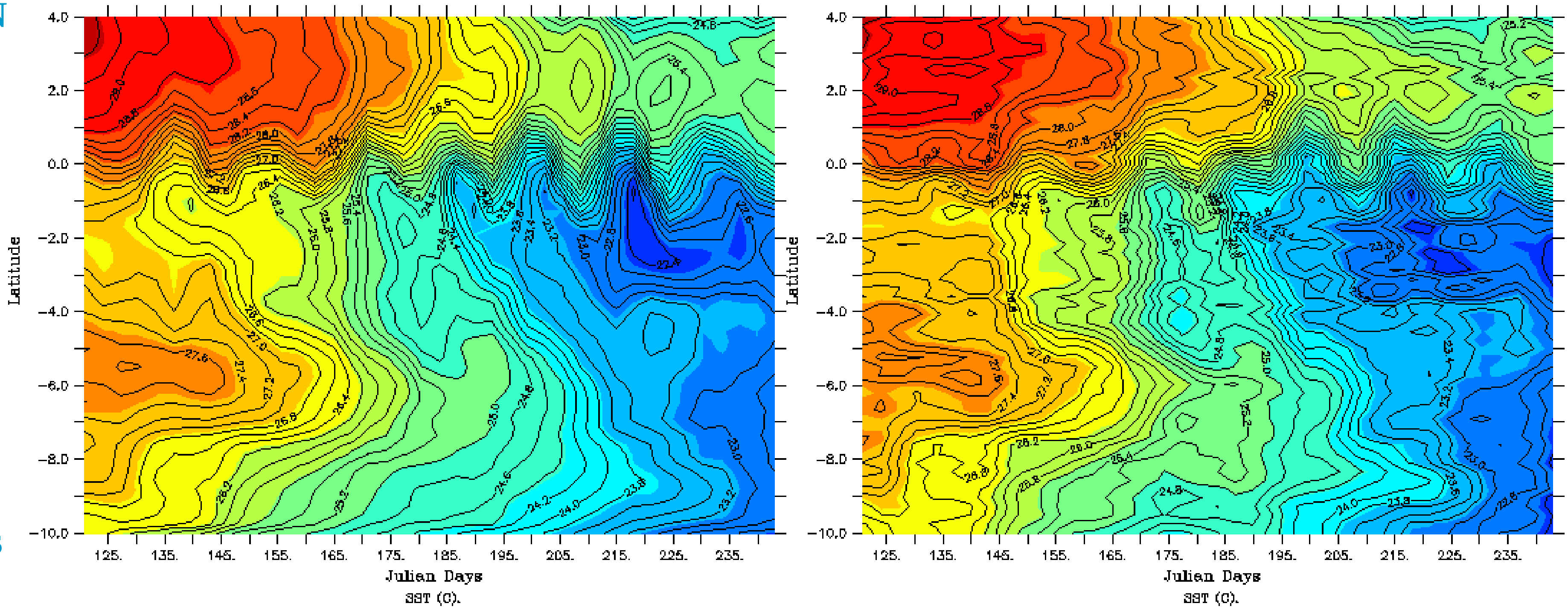
SST (0°W)

Model — Lannion

4 N

Eq

10 S



May — August

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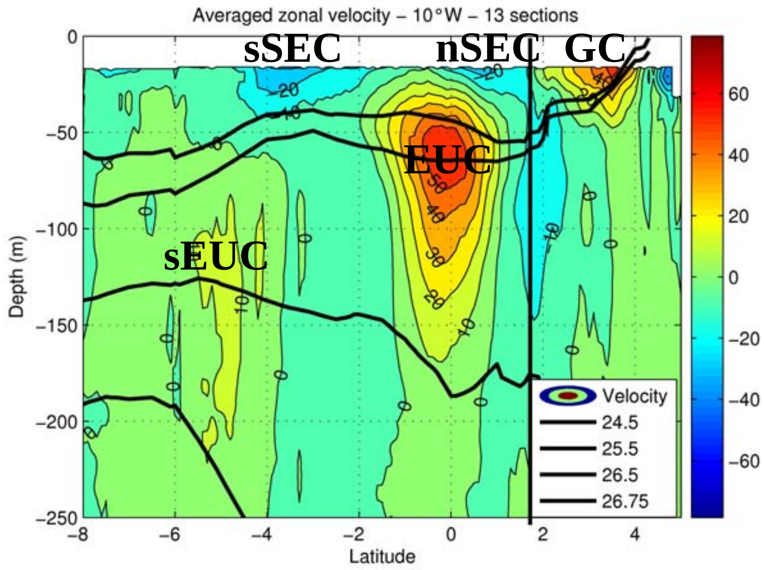
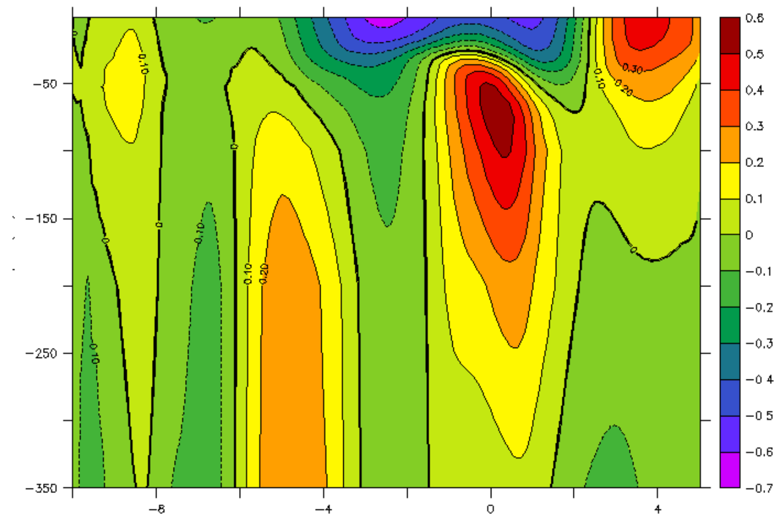
Validation

Observation-Mean EUC at 10°W
Courtesy B. Bourlès



Model



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How to identify the sources of vertical velocity ?

Ocean ß-plan slab model
(Zebiak and Cane, 1987)

$$\begin{cases} ru_s - \beta y v_s = \dfrac{\tau_x}{\rho_0 H} \\ \beta y u_s + r v_s = \dfrac{\tau_y}{\rho_0 H} \end{cases}$$

$$r = \frac{1}{\mathrm{T}}$$

Adjustment frequency of the Newtonian damping

Ekman Transport

$$\begin{cases} u_s = \dfrac{1}{\rho_0 H} \dfrac{r\tau_x + \beta y \tau_y}{r^2 + \beta^2 y^2} \\ v_s = \dfrac{1}{\rho_0 H} \dfrac{r\tau_y - \beta y \tau_x}{r^2 + \beta^2 y^2} \end{cases}$$

Current only induced by the surface stress τ
No vertical shear of the current

Ekman pumping

$$w(-H) = \frac{1}{\rho_0 (r^2 + \beta^2 y^2)} \left\{ \frac{\beta(\beta^2 y^2 - r^2)}{r^2 + \beta^2 y^2} \tau_x + \frac{-2\beta^2 y r}{r^2 + \beta^2 y^2} \tau_y + r \nabla . \tau + \beta y \nabla \wedge \tau \right\}$$

1 — Zonal stress
2 — Meridional stress
3 — Stress divergence
4 — Stress curl

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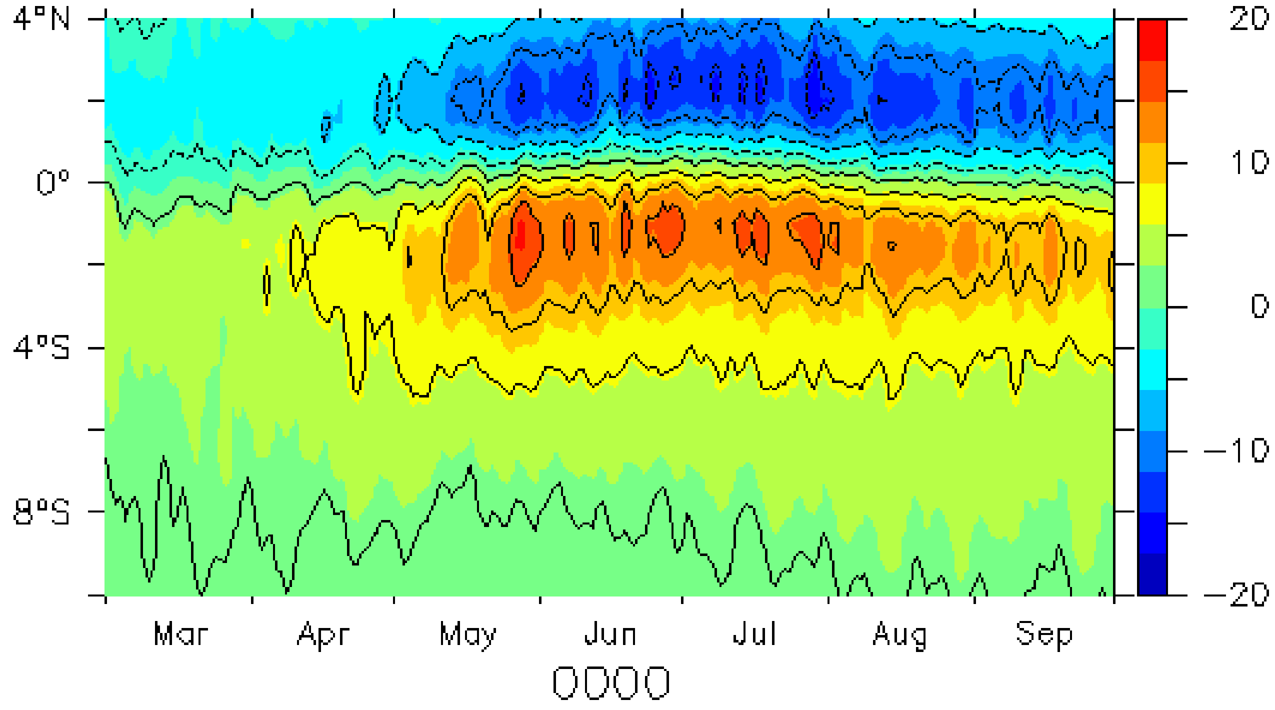

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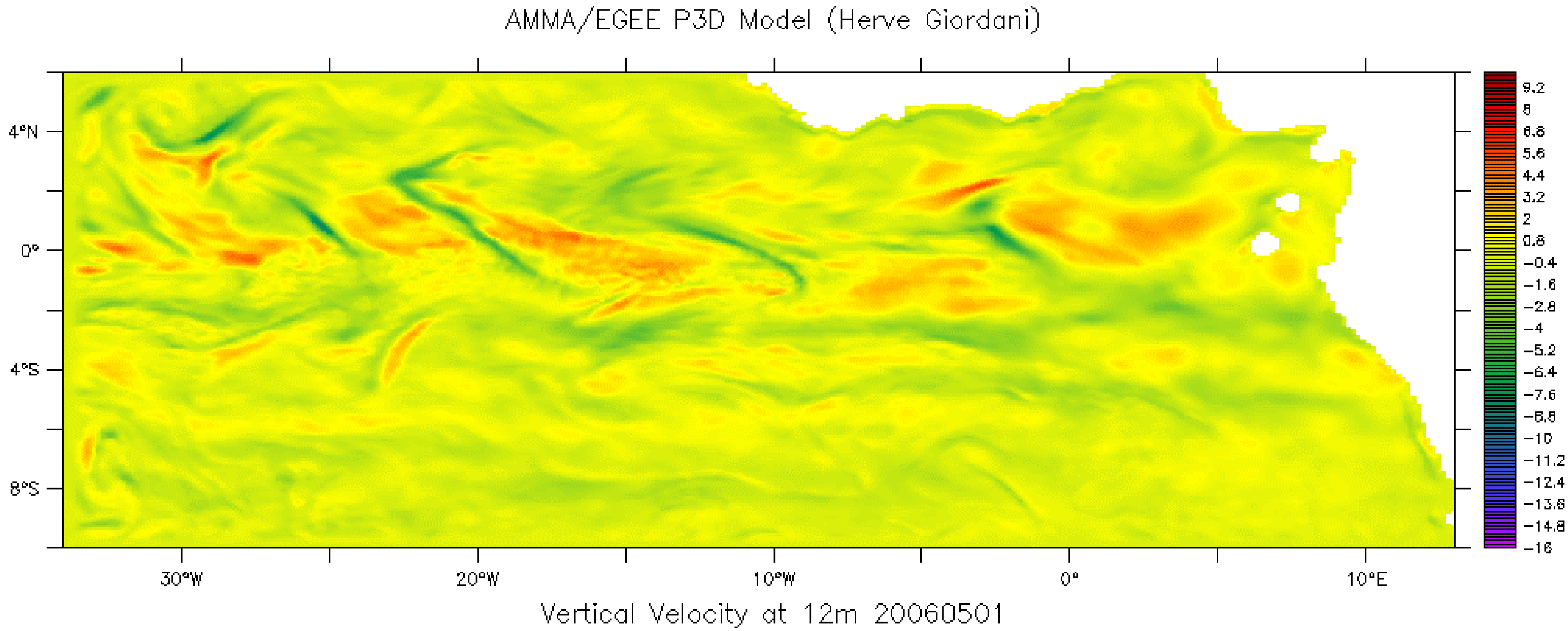
Simulation: MJJA 2006



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How to identify the sources of vertical velocity in the primitive equation system ?

$$\frac{\partial D}{\partial t} = f\xi - \beta u - \frac{1}{\rho}\nabla^2 P + \vec{\nabla}\left(\frac{\partial \vec{\tau}}{\partial z}\right) + Adv + Baro + Def$$

$$w(z) = \int_t \int_z \frac{\partial D}{\partial t} dz dt \Rightarrow \underbrace{w(H) = \frac{\partial D}{\partial t}\frac{H}{r}}_{Zebiak.and.Cane.(1987).approach}$$

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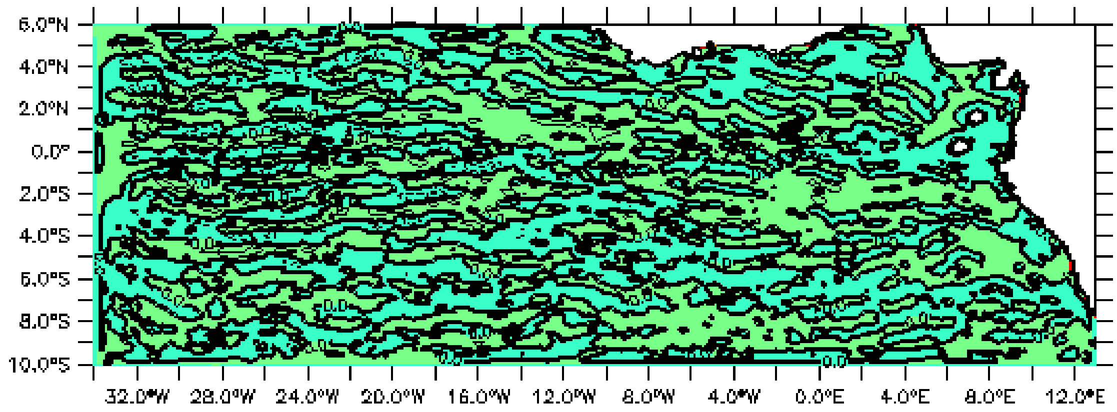
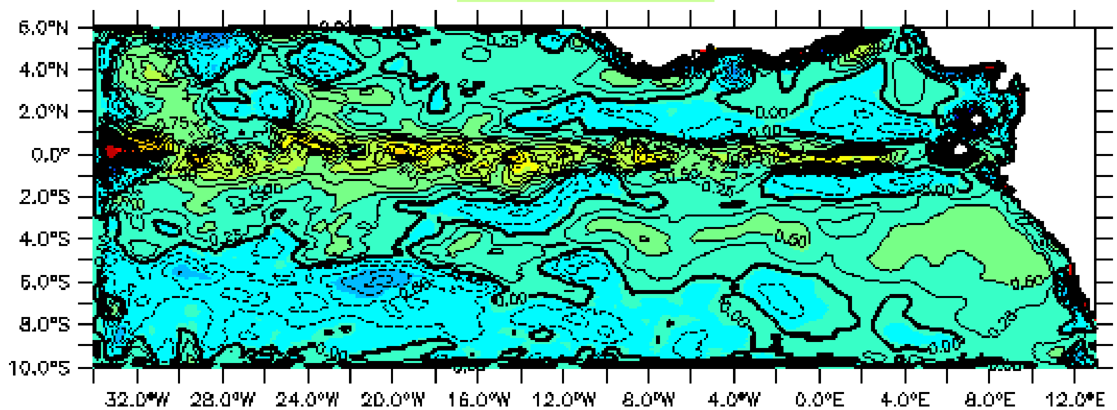
OUPS?



DW MODEL (mm/s)

W - May 2006



W MODEL (mm/s)

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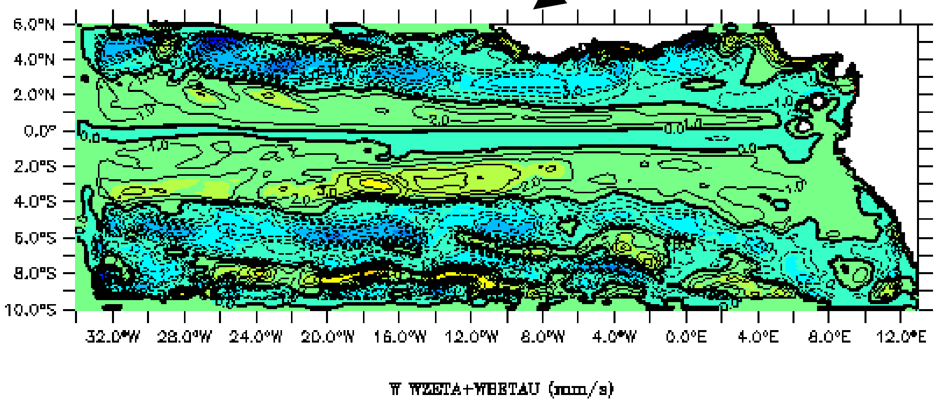
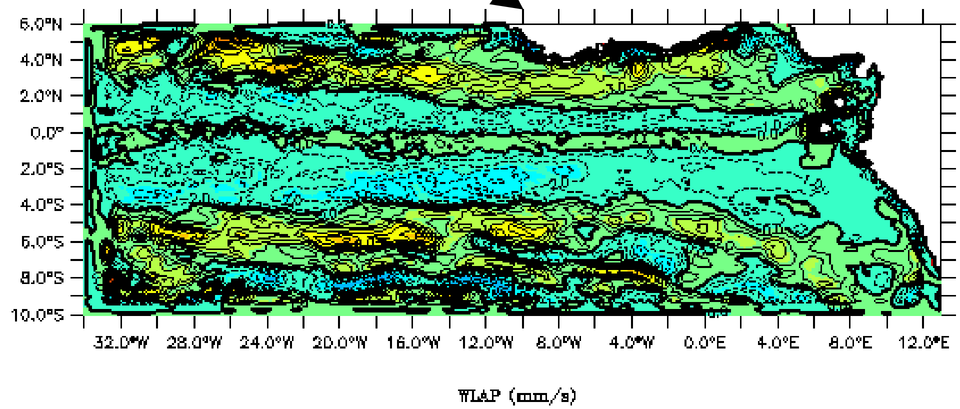
Is there an Equatorial balance?

$$\frac{\partial D}{\partial t} = \underbrace{f\xi - \beta u}\underbrace{-1/\rho \nabla^2 P} + \ldots$$





Yes !

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The Linear Equatorial Balance

$$\frac{1}{\rho}\nabla^2 P = f\xi - \beta u$$

$$\frac{\partial \xi}{\partial t} = -\beta v$$

$$\frac{\partial P}{\partial z} = -\rho g$$

$$\frac{1}{\rho}\nabla^2 \rho = \beta \frac{\partial u}{\partial z} + \beta f \frac{\partial v}{\partial z}\Delta t$$

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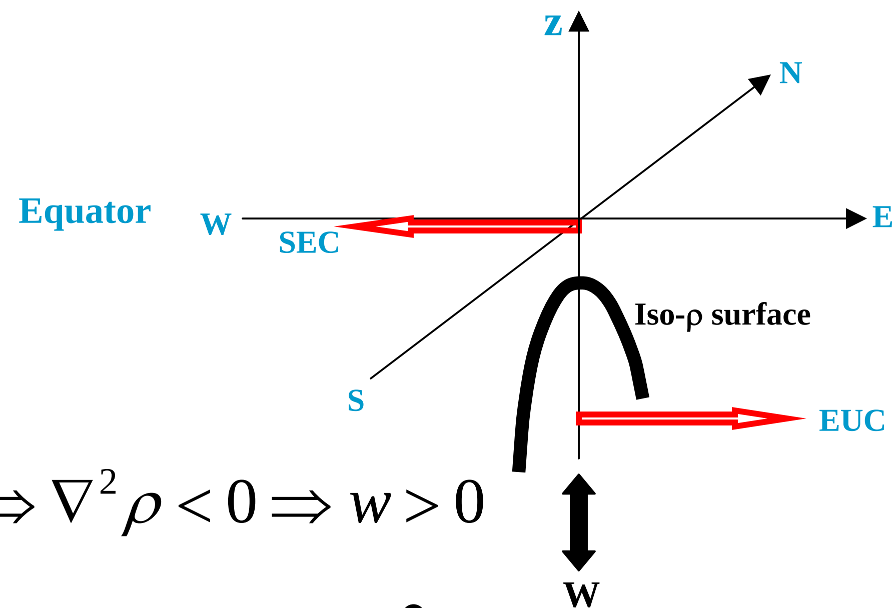
Vertical velocity inferred from the linear balance equation

$$\frac{1}{\rho}\nabla^2\rho = \beta\frac{\partial u}{\partial z} + \beta f\frac{\partial v}{\partial z}\Delta t - \frac{1}{h^2}\vec{\nabla}\vec{\tau}_s$$



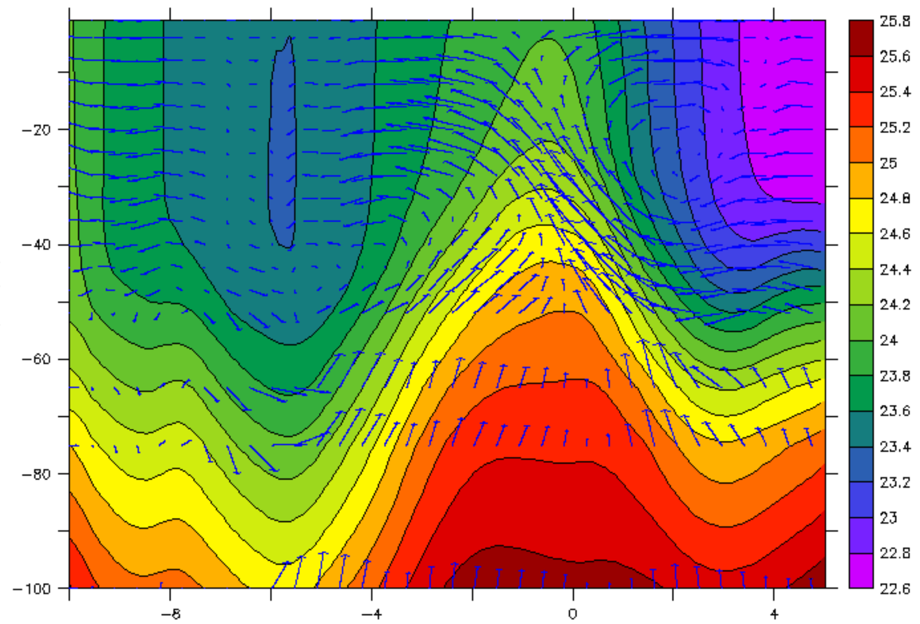
Upwelling Conditions:

Easterly Wind Pulse: $\tau_x < 0 \Rightarrow \beta\frac{\partial u}{\partial z} < 0 \Rightarrow \nabla^2\rho < 0 \Rightarrow w > 0$

Southerly Wind Pulse in the South Hemisphere: $\tau_y > 0 \Rightarrow \beta f\frac{\partial v}{\partial z} < 0 \Rightarrow w > 0$

Divergent Surface Stress: $\vec{\nabla}\vec{\tau} > 0 \Rightarrow w > 0$

w readjusts the density/pressure field to the circulation



Eq

The vertical velocity around the Equator restores the negative concavity of the density/pressure fields in order to sustain the vertical shear of zonal current

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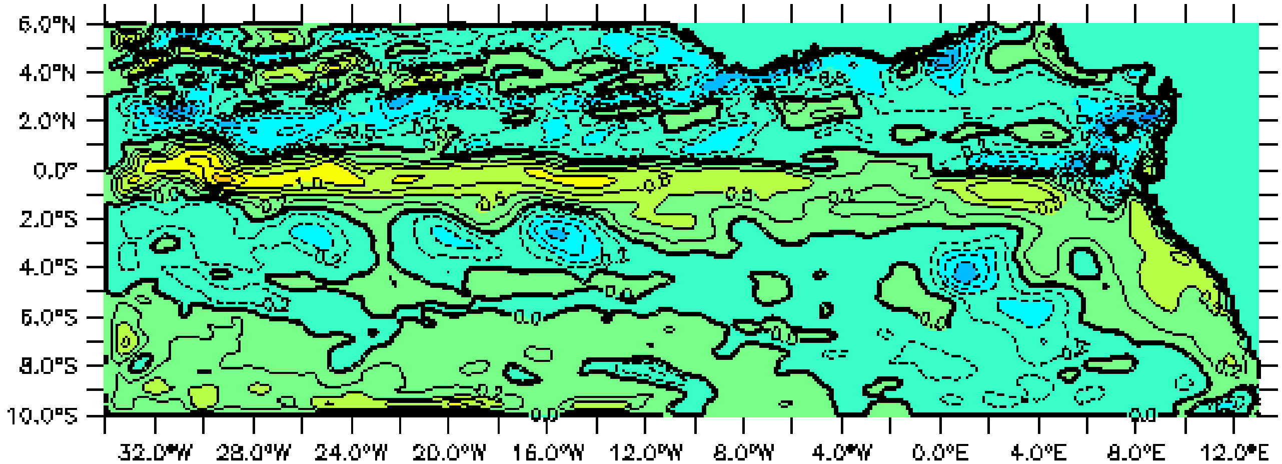
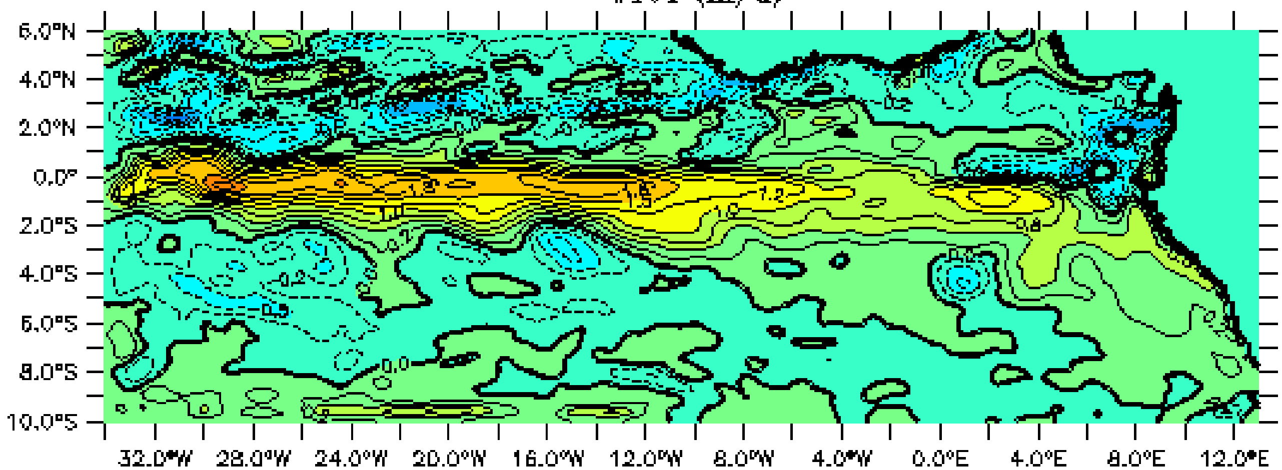
BINGO !



WTOT (m/d)



WMODEL (m/d)

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Generalized Vertical Velocity Equation

$$N^2\nabla^2 w + f(\xi + f)\frac{\partial^2 w}{\partial z^2} + \frac{1}{\mathrm{T}^2}\frac{\partial^2 w}{\partial z^2} + \beta\frac{\partial u}{\partial z}\frac{\partial w}{\partial z} + \left(\nabla^2 N^2 + \beta\frac{\partial^2 u}{\partial z^2} - f\frac{\partial^2 \xi}{\partial z^2}\right)w =$$

$$-\frac{\beta}{\rho}\frac{\partial}{\partial z}\left(\frac{\partial P}{\partial x}\right) - \frac{g}{\rho}\nabla^2\left[Advh(\rho)\right] + \frac{g}{\rho}\nabla^2\left(\frac{\partial F_\rho}{\partial z}\right) - f\frac{\partial Advh(\xi)}{\partial z} + \beta\frac{\partial Advh(u)}{\partial z}$$

$$+2\beta f\frac{\partial v}{\partial z} + \beta\frac{\partial^2 \tau_x}{\partial z^2} - f\vec{k}\Lambda\vec{\nabla}\left(\frac{\partial^2 \vec{\tau}}{\partial z^2}\right) - \frac{\partial}{\partial t}\left[\vec{\nabla}\left(\frac{\partial^2 \vec{\tau}}{\partial z^2}\right)\right]$$

$$-f\frac{\partial}{\partial z}\left[Baro(\xi) + def(\xi)\right] - \frac{\partial^2}{\partial t \partial z}\left[Adv(D) + Baro(D) + Def(D)\right] + \frac{\partial^3 D}{\partial t^2 \partial z}$$

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The ω-Response Function: An Elliptic Operator

$$\Gamma(w) = F \qquad \Gamma \Leftrightarrow r = 1/T$$

$$\Gamma = \left[N^2\nabla^2 + \nabla^2 N^2\right] + \left[f(\xi + f)\frac{\partial^2}{\partial z^2} - f\frac{\partial^2 \xi}{\partial z^2}\right] + \left[\beta\frac{\partial u}{\partial z}\frac{\partial}{\partial z} + \beta\frac{\partial^2 u}{\partial z^2}\right]$$

Pressure/Density | **Vorticity** | **Zonal Current**

The forcing associated with w works to balance its sources

$$\Gamma(w) = F \Rightarrow w = \Gamma^{-1}(F)$$

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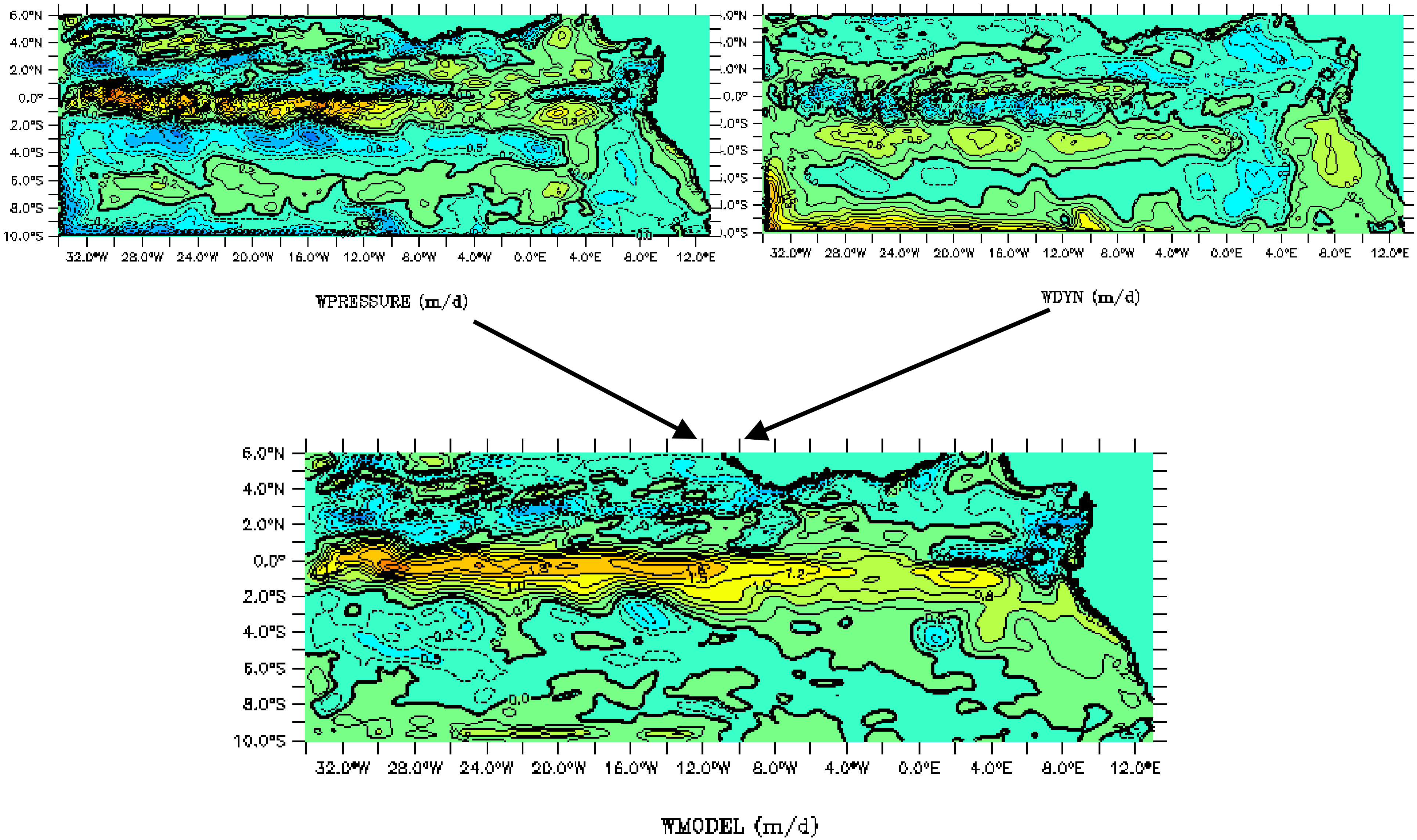
Thermodynamical   Dynamical



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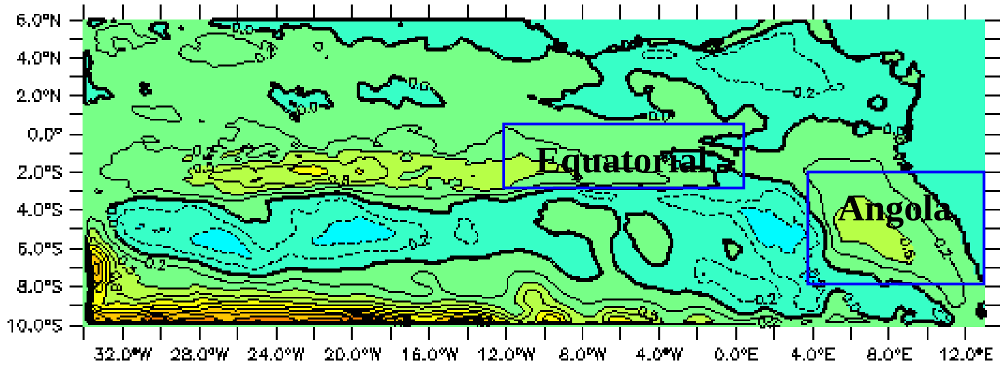
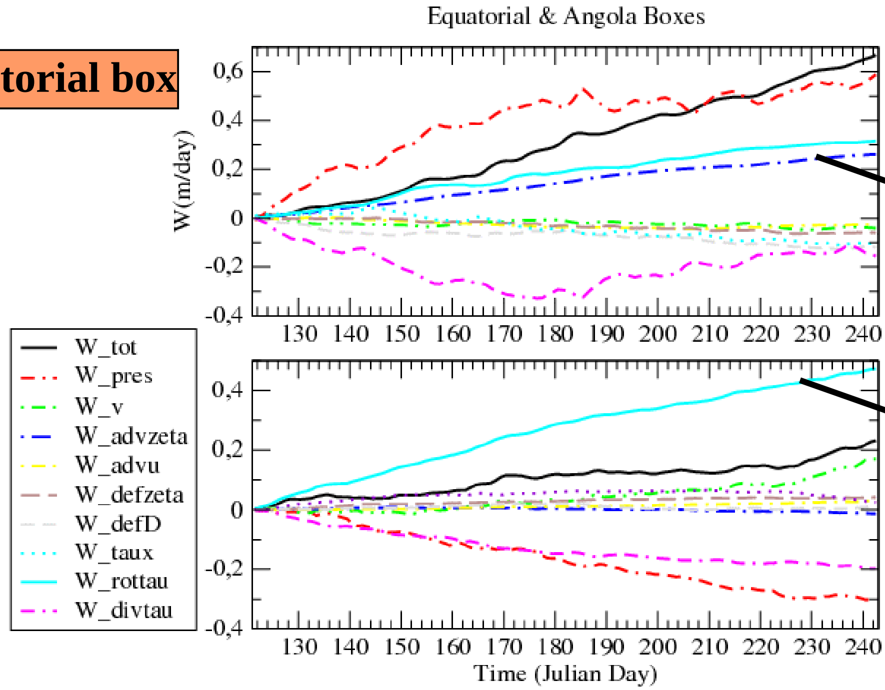
Curl of the momentum stress



Equatorial box

Angola box



Transport of ζ

Wind-Stress Curl

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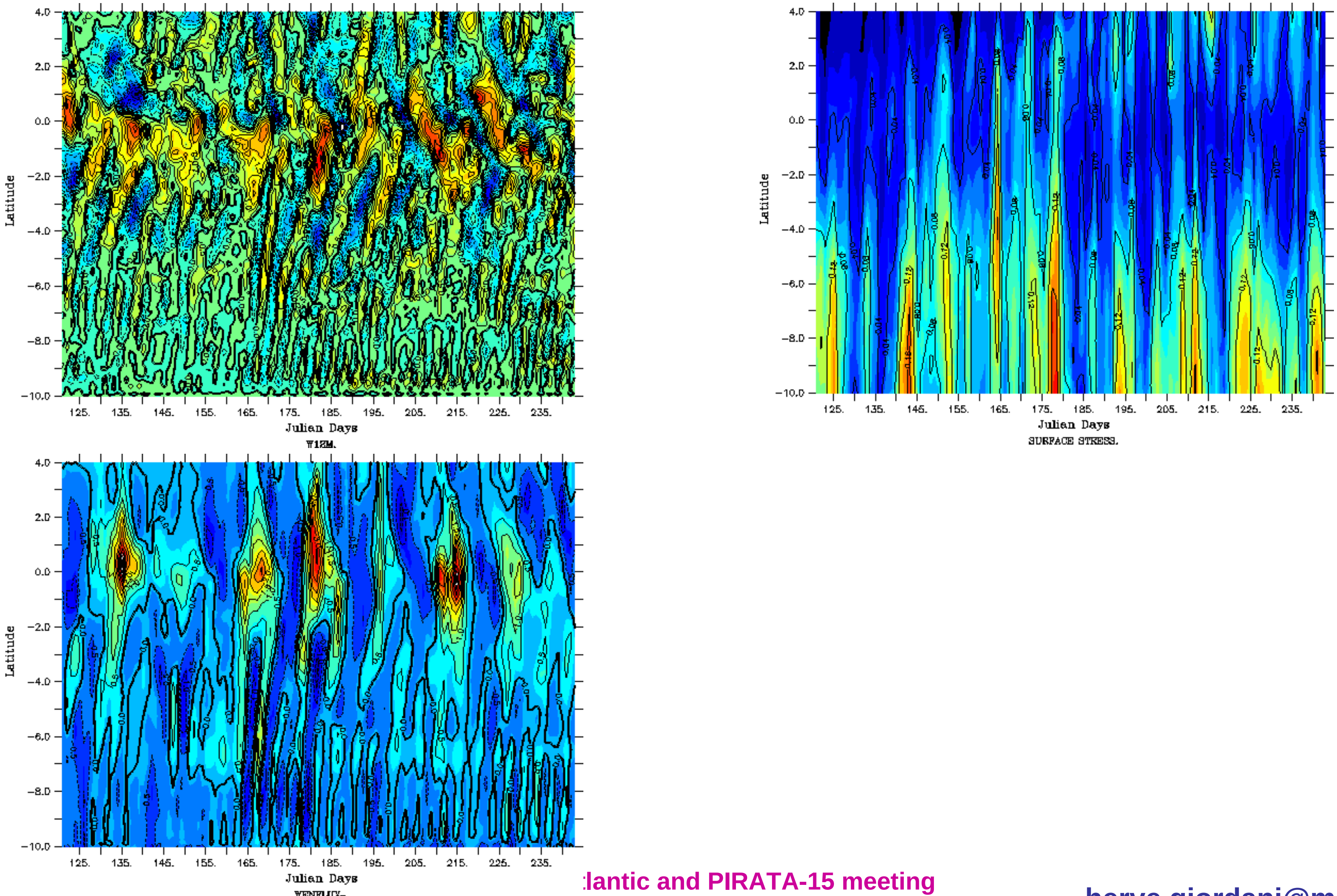
Vertical Velocity Hovmuller at 10°W



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Conclusion

1. The generalized ω-equation:

- The vertical velocity set up in order to restore the balance equation
- It includes the Ekman theory (Zebiak and Cane, 1987)
- Identification of the w-sources in the PE system

2. Equatorial upwelling adjusts the density/pressure fields to the sheared currents system
   $\Rightarrow$ Biases in OGCMs and OA coupled models ?

3. ω-equation: Indirect oceanic response to surface wind stress $\vec{\tau}$
   Ekman model: Direct response to $\vec{\tau}$

4. Upwelling of Angola results from the curl of momentum stress

5. Transport of vorticity: Connecting process between the Equatorial & Angola upwellings

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